Reconstructing orogens without biostratigraphy: The Saharides and continental growth during the final assembly of Gondwana-Land

A. M. Celâl Şengör[a,b,1], Nalan Lom[c], Cengiz Zabcı[b], Gürsel Sunal[b], and Tayfun Öner[d]

[a]İstanbul Teknik Üniversitesi (İTÜ) Avrasya Yerbilimleri Enstitüsü, Ayazağa 34469 İstanbul, Turkey; [b]İTÜ Maden Fakültesi, Jeoloji Bölümü, Ayazağa 34469 İstanbul, Turkey; [c]Departement Aardwetenschappen, Universiteit Utrecht, 3584 CB Utrecht, The Netherlands; and [d]Soyak Göztepe Sitesi, Üsküdar 34700 İstanbul, Turkey

Contributed by A. M. Celâl Şengör, October 3, 2020 (sent for review July 17, 2020; reviewed by Jonas Kley and Leigh H. Royden)

A hitherto unknown Neoproterozoic orogenic system, the Saharides, is described in North Africa. It formed during the 900–500-Ma interval. The Saharides involved large subduction accretion complexes occupying almost the entire Arabian Shield and much of Egypt and parts of the small Precambrian inliers in the Sahara including the Ahaggar mountains. These complexes consist of, at least by half, juvenile material forming some 5 million km^2 new continental crust. Contrary to conventional wisdom in the areas they occupy, evolution of the Saharides involved no continental collisions until the end of their development. They formed by subduction and strike-slip stacking of arc material mostly by precollisional coastwise transport of arc fragments rifted from the Congo/Tanzania cratonic nucleus in a manner very similar to the development of the Nipponides in east Asia, parts of the North American Cordillera and the Altaids. The Sahara appears to be underlain by a double orocline similar to the Hercynian double orocline in western Europe and northwestern Africa and not by an hypothetical "Saharan Metacraton." The method we develop here may be useful to reconstruct the structure of some of the Precambrian orogenic belts before biostratigraphy became possible.

Turkic-type orogenesis | continental growth by subduction-accretion | Saharides | Gondwana-Land | Africa

A major, hitherto unrecognized, Neoproterozoic orogenic system, the Saharides (1) (Fig. 1 and *SI Appendix*, Fig. S1), is described in North Africa and Arabia that formed from about 900–500 Ma ago culminating in the final collision between east and west Gondwana-Land. The Saharides involved major subduction accretion complexes occupying almost the entire Arabian-Nubian Shield and much of the Sahara. They have the form of a double orocline much like the Hercynian double orocline in western Europe and northwestern Africa.

Reconstructing complexly deformed orogenic regions during the Precambrian has proved a major challenge and led to controversies even about the overall tectonic behavior of the earth in pre-Phanerozoic eras (e.g., refs. 2–8), largely because of the great difficulty, in places outright impossibility, of making detailed structural analyses (9) and long-range stratigraphic correlations (see the "marginal notes" in ref. 10). Consequently, reconstructions of the structure and evolution of Precambrian orogenic belts of the kind published by Hildebrand et al. (11) are very rare and wholly undertaken on orogens of a relatively simple architecture. A knowledge of the global orogenic evolution in the Precambrian is, however, among the first desiderata for the solution of a number of problems about the evolution of our planet, such as paleogeography, paleoclimate, and evolution of life in those remote times in earth history (12, 13).

There is now little disagreement that during the Neoproterozoic plate tectonics was operative and yet life had not evolved to a point to make biostratigraphy feasible. Therefore, in the areas we selected, geological processes can be assumed to have been almost identical to those now operating (the snowball earth and the absence of land flora were the main deviating factors), yet the dominantly biostratigraphy-based methods used to untangle orogenic evolution during the Phanerozoic are not applicable to them.

Method of Reconstructing Complex Orogenic Evolution in the Neoproterozoic without Biostratigraphy: Example of the Saharides

Suess (1) named a north–south-orientated orogenic belt located adjacent to the eastern margin of the West African Craton the "Saharides." Soon afterward, Kilian (14) showed that Suess' Saharides were in fact Precambrian in age. Later work has revealed that rocks and events similar to those exposed in Suess' Saharides were widespread in the entire Sahara and the Arabian Peninsula (e.g., refs 15–23; also see refs. in *SI Appendix*; in our rock descriptions in *SI Appendix* we report rocks as they appear on the outcrop without "correcting: to protoliths in case of metamorphic rocks"). The development of reliable isotopic age-dating methods with small error margins has led to a flurry of age dating in these regions, but, despite much geological field mapping and age dating, no unified structure for the entire area and no scenario for paleotectonic evolution displayed in time-lapse frames have yet emerged. The main reason for this has been that the outcropping parts in the entire area were divided into

Significance

A method without biostratigraphy is employed to delineate a hitherto unknown, major orogenic system of Neoproterozoic age in North Africa and Arabia in which some 5 million km^2 of juvenile continental crust may have been generated in some 400 Ma, i.e., 0.44 km^3/a assuming a minimum thickness of 35 km for the generated crust, thus slightly less than the 1/3 of the annual average crustal growth rate globally and similar to the crustal growth rate in the Altaids of Asia between 600 and 140 Ma, supporting the idea that the formation of the continental crust has been continuous throughout earth history, albeit with fluctuating intensity. Our method can be applied to reconstruct other complex Precambrian orogenic systems.

Author contributions: A.M.C.Ş. designed research; A.M.C.Ş., N.L., C.Z., and G.S. performed research; A.M.C.Ş., N.L., C.Z., G.S., and T.Ö. contributed new reagents/analytic tools; A.M.C.Ş., N.L., C.Z., and G.S. analyzed data; A.M.C.Ş. wrote the paper; and N.L., C.Z., and G.S. provided critical feedback and helped shape the research and manuscript.

Reviewers: J.K., Georg-August-Universität Göttingen; and L.H.R., Massachusetts Institute of Technology.

The authors declare no competing interest.

[1]To whom correspondence may be addressed. Email: sengor@itu.edu.tr.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2015117117/-/DCSupplemental.

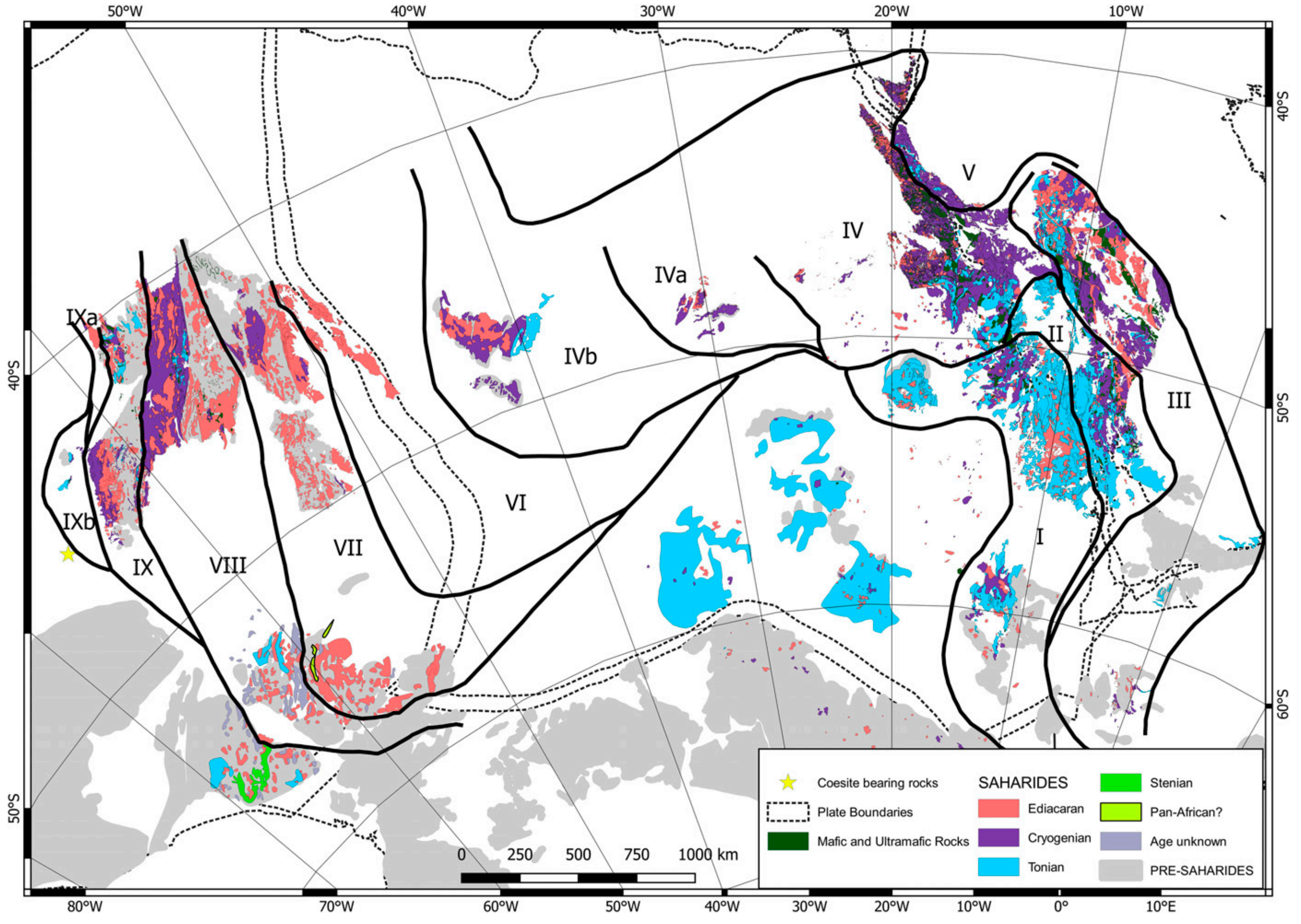

Fig. 1. Map of the Saharides, which was made on a reconstructed north Africa/Arabia ensemble using the data reported in *SI Appendix*, Tables S1 and S2. Please see *SI Appendix*, Fig. S1 for the full tectonic map displaying the distribution of units and their tectonic environments. GPlates freeware (55) was used for the reconstruction. Four hundred forty five Ma reconstruction, as proxy to the Ediacaran reconstruction data from ref. 54.

innumerable "terranes" on the basis of diverse criteria, such as stratigraphic sequence, rock type, metamorphic grade, and structural style, yet little correlation between them to erect an overall architecture has been attempted. Such terranes were assumed to have been independent entities housing a number of hypothetical island arcs, metamorphic massifs, or sedimentary basins that had been brought together via numerous postulated, but not documented, collisions (so-called "overlap assemblages" are often employed as the only criterion for establishing a collision), at the expense of presumed oceans, although no reconstruction of their tectonic evolution has yet emerged. This methodological blind alley of "terranology" was exacerbated by the paucity of outcrop in vast areas in the Sahara. In addition, all metamorphic outcrop areas older than about 900–600 Ma in the Sahara have been assumed to form parts of what is called a Saharan metacraton (23, 24), a hypothetical entity reaching from Egypt to Mali and Algeria and believed to have fallen apart to give rise to some deformation internally, yet providing firm buttress to orogenic events around its periphery. No mechanism has been proposed for its dissolution except spontaneous lithospheric mantle delamination (25), for which there is neither a viable mechanism at this scale, nor an actualistic analog. Small pieces of craton have indeed been destroyed by heating from below by arc magmatism as in North China and in Wyoming, Colorado, and New Mexico, but both these areas are incomparably smaller than the Sahara with direct access to subduction zones.

Such models have since led to a number of internal inconsistencies: the postulated island arc terranes are impossibly smaller than the present-day arcs such as those of the Japanese islands (an ensialic arc: about 9.20×10^5 km^2) or the Marianas (an ensimatic arc essentially with no subduction–accretion complex: about 3.5×10^5 km^2); any single one of these would take up much of the volume of the Arabian-Nubian Shield (about 1.4×10^6 km^2). Assumed collisional sutures between terranes have none of the earmarks of the present-day collisional systems such as flanking magmatic arcs, shortening-related metamorphic cores, and attendant fold-and-thrust belts behind flexural molasse basins; at least two basins identified as molasse basins in the Arabian-Nubian Shield (15, 17, 18) not only lack accompanying structures, but have widespread calc-alkalic magmatism ranging from mafic to felsic intrusions and volcanics, not known from any Phanerozoic, orogen-marginal, molasse environment. In no cross-section in the entire Saharides can an intact island arc be reconstructed and the hypothesized magmatic island arcs seem to be only fragments of former arcs or indeed of a single, dismembered arc. Within the presumed Saharan "metacraton" subduction-related magmatism appears to have gone on during the entire evolution of the Saharides from about 900 to 500 Ma, contradicting the very concept of a craton, or indeed a metacraton (see our Fig. 2).

In order to resolve such apparent contradictions we have decided to reconstruct the tectonic environments of the Saharides

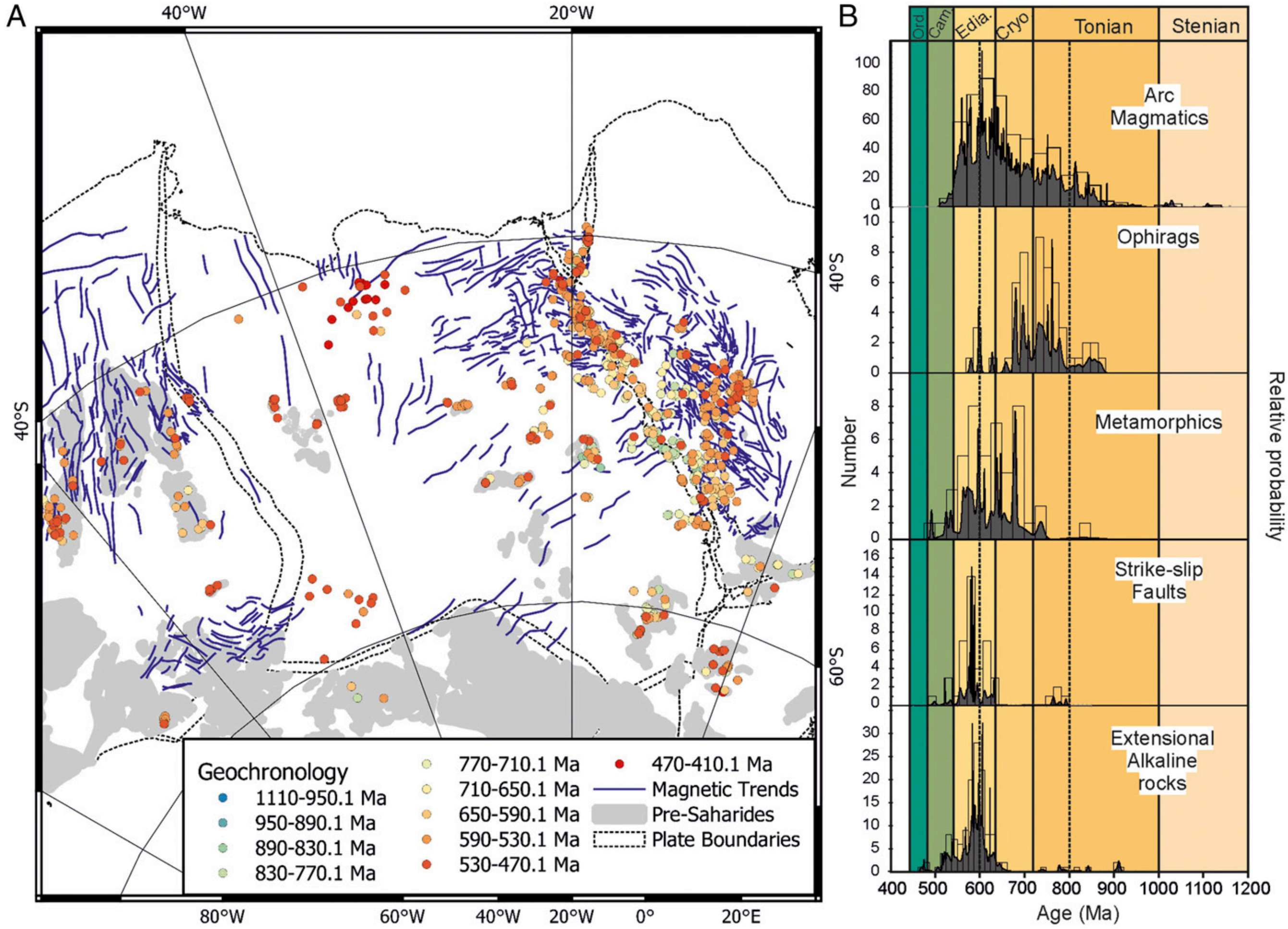

Fig. 2. (*A*) Map showing schematically the magnetic lineations (in dark blue) in the area of the Saharides and the locations of the points from which we report isotopic ages. For data details and sources see *SI Appendix*. (*B*) Histograms showing the isotopic ages of rocks representing distinct tectonic environments. Ophirags are fragments of ophiolites that have been dismembered in subduction zones, along collision fronts or along major strike-slip faults (56).

that are familiar from the Phanerozoic orogens, such as magmatic arcs, forearc accretionary complexes and forearc basins perched atop them, various rear-arc environments, pieces of older continental crust and large fault belts using sedimentology, igneous and metamorphic petrology, geochemistry and structural geology as revealed by the available rock record and the high-quality isotopic age distribution within it (*SI Appendix*, Table S1). We used published geochemical assessments to distinguish juvenile versus reworked crustal pieces paying attention to what mineral was used as material. Collisional versus subduction distinction using geochemistry alone is simply not possible in evolved arcs owing to preexisting mantle and crustal histories, so we ignored any claims made on tectonic environments that employed geochemical data alone. It is critical to emphasize that once a tectonic environment is identified, it implies the existence of others related to it: for instance, a magmatic arc axis must have associated forearc and back arc structures, even if they may now appear elsewhere due to later displacement. Our purpose was to identify what we call the essential orogenic units, such as magmatic arcs, suture zones, continental margins with attendant environments, without which an orogen cannot exist, and major fault zones displacing them in toto or only partially. This procedure, a kind of comparative anatomy of orogens, brings with it the necessity to circumscribe what we call accidental orogenic units, i.e., those formed by the caprices of the ongoing deformation (analogous to broken and scattered bones of fossil vertebrates), such as strike-slip duplexes, major nappes, normal-fault-bounded rock packages. The essential units may be chopped up into accidental units while their essential tectonic evolution is still ongoing: For example, a forearc accretionary complex or an entire forearc basin may be faulted away from its parent arc while subduction is still active, as for instance in Sumatra along the Sumatra Fault and its splays such as the Batee Fault (26, 27).

A fundamental assumption of our method is the continuity, both in time and space of major subduction zones. All of the subduction zones today are continuous for thousands of kilometers and have persisted for more than 200 Ma with the exception of remnant subduction zones in areas of complex continental collision such as the Mediterranean or Southeast Asia. The spatially small subduction zones in such places are remnants of originally long ones parceled up by intervening collisions and they are all short-lived (e.g., ref. 28).

Where outcrop is rare, as in vast tracts of the Sahara, we used the available geophysical information, particularly the magnetic anomalies (29–31), to trace our units at depth connecting the scattered outcrops (Fig. 2). Magnetic anomalies are especially suitable to trace arcs and accretionary complexes because of the abundance of iron-rich minerals in them. The overall method we use is akin to the one we employed to reconstruct the largest orogenic collage in Asia, namely the Altaids (32, 33), differing from it significantly, however, by the complete absence of biostratigraphy and the paucity of outcrop in much of the Saharides.

Saharides: Definition

The Saharides are an hitherto unrecognized [except a tiny strip in the extreme west by Suess (1), which he could not relate to anything to the east], major orogenic collage of Neoproterozoic Age. It extends from the Ahaggar Massif in the west to almost the Persian Gulf in the east and from the Mediterranean shores of Africa to the Sahel, thus encompassing almost the entire Sahara and the Arabian-Nubian Shield (Fig. 1 and *SI Appendix*, Fig. S1). Its best exposures are found in the latter area, whereas in the Sahara the areas where it comes to surface are limited and confined to such outliers as Jebel Uweynat (34), Tibesti (16), and Ahaggar (19). We have defined the essential orogenic units on the basis of the available surface information culled from the literature (summarized in refs. 15–23 and those in *SI Appendix*, Table S2) and the strike lines, which were traced on Google Earth. We also cross-checked our mapping with the published information (Fig. 1 and *SI Appendix*, Fig. S1). We recognize in the Arabian-Nubian Shield five distinct accidental tectonic units representing parts of a single dismembered magmatic arc (denoted by I–V in Fig. 1), an essential orogenic unit of Late Tonian to Ediacaran Age, in which the arc massif carrying the magmatic arc axis, a well-developed forearc subduction–accretion complex and various bits of an extensive forearc basin could be identified (*SI Appendix*, Table S1). In Fig. 3, we have reconstructed that arc by correlating the magmatic axis distributed in its now disjointed parts and drew the magmatic fronts of Tonian, Cryogenian, and Ediacaran ages. The alignment of the units was done by correlating their geological environments and, critically, the magmatic fronts used as structural markers to yield tie points, which were then checked with surrounding geology to corroborate the correlation. The remarkable continuity not only of the geology (rock types, structures, and timing), but also of the magmatic fronts and the unity in their movements in time with respect to the original arc massif in the reconstructed arc gave us further confidence about our reconstruction. The age of disruption of the arc by left-lateral arc-slicing strike-slip faults is almost entirely Ediacaran (Fig. 2).

Tracing the arc into the Sahara by using the very scanty outcrops alone is not safe. That is why we have compiled the available magnetic data from the entire corpus of the Saharides (Fig. 2). The trends of the magnetic lineations are parallel to subparallel with the strike lines of the Saharides in the scattered outcrops (compare Fig. 2 and *SI Appendix*, Fig. S1) defining a south-concave orocline in the Sinai Peninsula and the northeasternmost corner of Africa. Moreover, the Mesozoic rifts under the Sahara also follow the magnetic anomalies. The rifts themselves do not cause the anomalies, because elsewhere, for example in Kenya, the Pan-African trends cross-cut the Anza Rift (29), yet the magnetic anomalies follow the orogenic trend and not the taphrogenic one. It has long been known, particularly by petroleum geologists, that the younger rifts in the Sahara follow the older Pan-African structures (35, 36). The structural trends we mapped and the trends of the magnetic lineations allowed us to show that under the Sahara the orogenic trend lines turn in such a way as to define a second, but north–north–east concave, orocline between Tibesti and Nigeria (37). The outcrops in the Ahaggar Massif and Nigeria and the sparse magnetic lineations between them gave us some control on the placement of the boundaries of the units VI through IX in the western Saharides.

Despite the paucity of surface data, we separated units VI through IX, because if it were assumed that units IV and V continue into the central Sahara intact, the arcs would have assumed unrealistic widths. Moreover, both in Nigeria and in the Ahaggar, outcropping arc environments repeat across the strike (*SI Appendix*, Fig. S1), indicating horizontal stacking along strike-slip faults that repeat units across their strike. We think the geometry of units depicted in Fig. 1 is the optimum interpretation now allowed by the available observations.

Once it was seen that in the Arabian Nubian Shield only a single arc satisfies the observations, we extended that interpretation and constructed a single magmatic arc from the Ahaggar to Arabia, named the Tuareg Arc, after the oldest inhabitants of the Sahara (Fig. 4*A*). This arc has both pieces older than the Saharide evolution (e.g., in units III?, IV, VI, VII, VIII, and IX), which serve in places as Saharide arc massifs (e.g., in units III?, IV a, VII, VIII, and IX) and those almost entirely of Saharide age (e.g., in units I–V with possible exception of unit III). Some

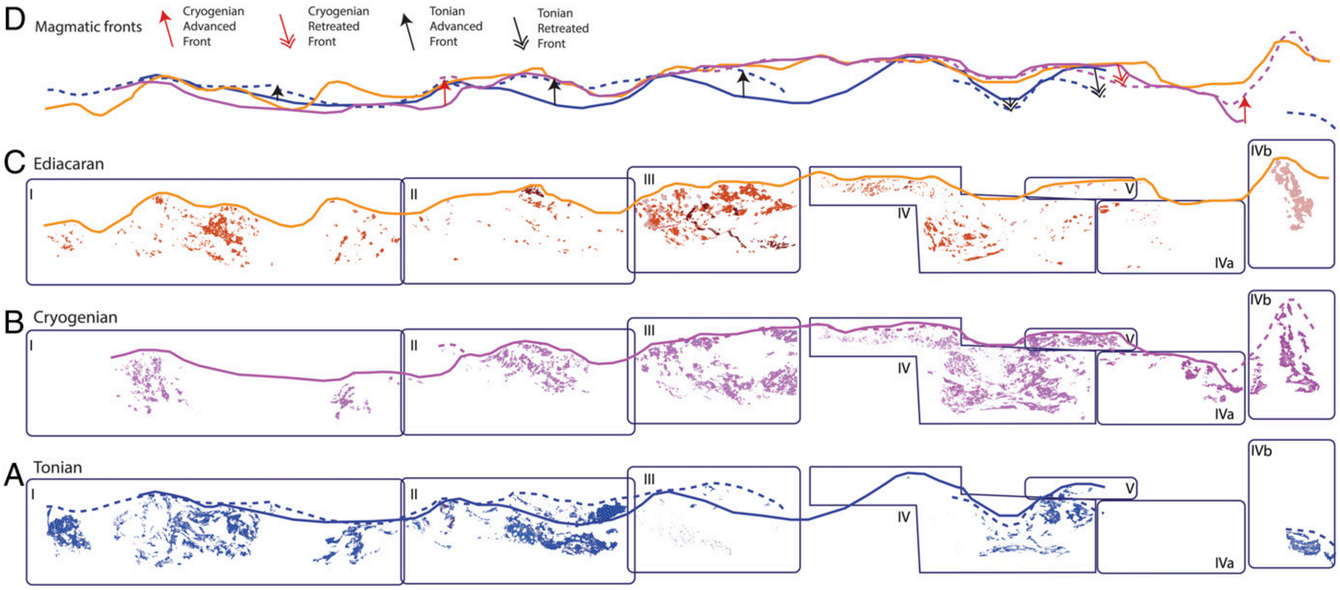

Fig. 3. Tonian (*A*), Cryogenian (*B*), and the Ediacaran (*C*) magmatic fronts of the units I-V. Notice their spatial and temporal continuity in the reconstructed arc (*D*). Paucity of outcrop makes drawing similar fronts for the rest of the Saharide units not feasible for the time being.

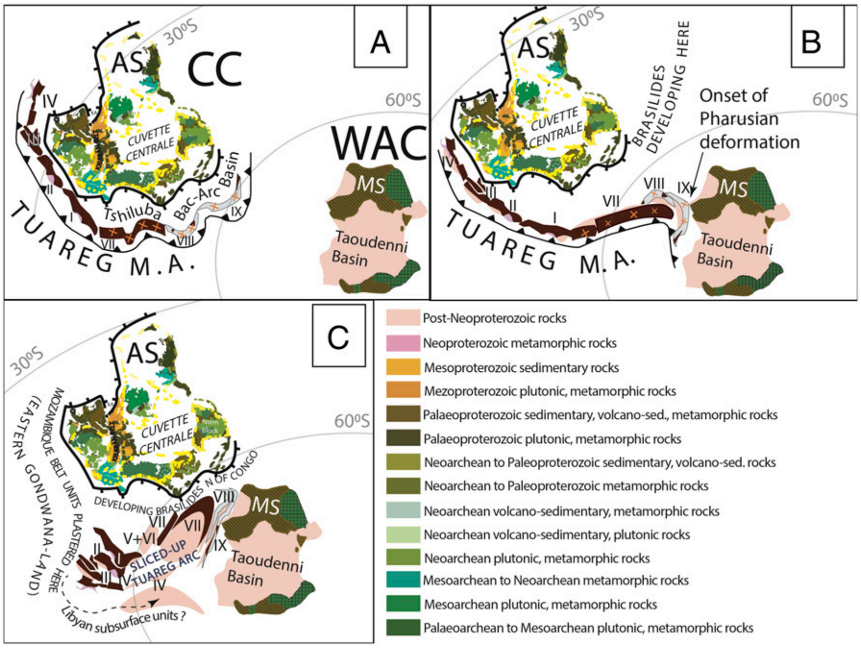

Fig. 4. Three time-lapse frames showing the paleotectonic evolution of the Saharides. The Roman numerals correspond to the accidental unit numbers. (*A*) The reconstruction of the Saharides at the beginning of the Neoproterozoic. (*B*) The Saharides during the Cryogenian. (*C*) The Saharides during the Ediacaran. Key to abbreviations: CC: Congo Craton, WAC: West African Craton, MS: Man Shield.

of the juvenile forearc units (e.g., unit V) were strike-slipped away from their parent arc and were inserted between arc segments separated by strike-slip faults that cut out units across their strikes, thus lengthening the original Tuareg Arc.

Saharides: Evolution

The existence of older continental material in the Tuareg Arc makes it likely that at least those parts probably rifted from an older continent. The age distribution of the pre-Saharide fragments in the Tuareg Arc point to the Congo-Tanzanian craton as a possible parent continent (38). When the Tuareg Arc is placed on it, the length of the arc corresponds almost exactly to the total length of the eastern and northern margins of the craton indicating that they are a plausible location for its origin. Evidence of coeval rifting both on the Congo-Tanzanian Craton and the Tuareg Arc exists as alkalic rocks along their assumed facing margins that are about 1 Ga old (39, 40), indicating the time when the Tuareg Arc parted company with the parent continent as a migratory magmatic arc (Fig. 4*A*). This is corroborated by the presence of some Tonian strike-slip ages within the Tuareg Arc (Fig. 2).

Near the end of the Cryogenian, the westernmost part of the Tuareg Arc collided with the West African Craton giving rise to the Pharusian orogeny (41) (Fig. 4*B*) during which subduction-related slivers of coesite-bearing rocks came to the surface (42). This collision and the ongoing approach of the Congo-Tanzanian and the West African cratons (43) led to the internal slicing of the Tuareg Arc and its double oroclinal bending much like the western segment of the Hercynides in Europe (Fig. 4*C*).

Our interpretation shows that, with the exception of the Pharusian point collision, there were no continental collisions in the entire evolution of the Saharides until the final suturing of east and west Gondwana-Land in the latest Ediacaran-earliest Cambrian. This inference is corroborated by the great paucity of late Saharide-age (younger than 700 Ma) zircons in the Phanerozoic deposits of the entire Sahara suggesting the absence of eroding high mountain ranges (44–46). Even today, the Saharide lithosphere is unusually thin, rising to a maximum of some 120 km in a small area northwest of Kufra, but remaining mostly around 70–80 km on the basis of surface waves (e.g., refs. 47 and 48), notwithstanding one claim to the contrary (49). Once the Saharide evolution was completed by the tightening of the oroclines caused by the late Neoproterozoic to Cambrian intra–Gondwana-Land collision along the Mozambique suture extending from Antarctica to Arabia (50), alkalic magmatism invaded major parts of its area possibly caused by the detachment of the Saharide subduction slabs, much like the final Permian A-type granite invasion in the Altaids (32, 33). To the north of the Saharides, a continental margin magmatic arc along the now-amalgamated Gondwana-Land northern edge, called the Protogonos Arc, began its activity that would go on to create the Hercynides and the Cimmerides during the course of the Phanerozoic (51). The abundance of magmatic zircons in the Cambrian sediments in Europe is evidence for the existence of major mountains associated with this continental margin magmatic arc resembling the present-day Sumatra or even the Andes.

Implications

Reconstructing Complex Orogenic Collages in the Precambrian. Describing past orogens in terms of the tectonic environments known from Phanerozoic orogens, however disrupted they may be later, allows inference of structural continuity and reconstruction of their structure. This method enables the geologist, in the absence of biostratigraphy, to attempt long-distance correlations of such apparatuses as magmatic arcs and associated family of environments, in sharp contrast to the recommendations of terranology which end up creating numerous mute geographical entities impeding searches for original continuity among them (52). The method followed herein seems a powerful tool to reconstruct complex Precambrian orogenic collages and trace their evolution in time. What is needed for this method are reliable geological field data, high-quality isotopic ages tied to the field data and, where needed, subsurface geophysical data to follow orogenic trends in places of scant outcrop.

Continental Growth. The Saharides seem to have added a minimum of some 3–5 million km^2 of juvenile material to the continents by means of subduction–accretion fed by ensimatic portions of a magmatic arc in some 400 Ma, i.e., 0.44 km^3/a assuming a minimum thickness of 35 km for the generated crust, thus slightly less than the 1/3 of the annual average crustal growth rate globally and similar to the crustal growth rate in the Altaids of Asia between 600 and 140 Ma. This estimate is an absolute minimum, because of the paucity of outcrop in the Sahara, but it seems that the Saharides, almost exactly as large as the Altaids, may have added a similar amount of new material to the continents during their evolution. This shows that subduction–accretion may be one of the most important, if not the most important, means of enlarging the continental material on our planet and there is no need for mantle plumes (52) in areas of the growth of accretionary prisms in front of arcs to supplement their contribution; their growth rate may be as fast as >2.5 million km^3/140 Ma in the present-day Makran (53).

Continental Reconstructions. Continental reconstructions are almost always done on the basis of paleomagnetic and biogeographical data using their present shapes or cutting up those shapes along presumed collisional sutures taken as lines (e.g., refs. 43 and 54). Work both in the Altaids (32, 33) and on the Saharides shows how misleading such a procedure must be. Before any global reconstruction is attempted, the strain history of the orogenic systems separating cratonic areas ought to be established lest unrealistic paleogeographies are obtained. Reconstructing the strain history in orogenic belts may even help establish latitudinal control for the flanking cratons, as arc "bridges" such as the Kipchak in the Altaids and the Tuareg in the Saharides may provide maximum separation distances between former continents along the parallels and timing and magnitude of the change that distance may undergo.

Data Availability. All study data are included in the article and *SI Appendix*.

ACKNOWLEDGMENTS. We thank Jean-Paul Liégeois and Peter R. Johnson for sending us data and Anke Friedrich and Abdelrahman Khalifa for providing access to some regional maps, some of which were digitized by Mehran Basmenji and Müge Yazıcı. We are thankful to Wim Spakman for his comments on seismic tomography. The İstanbul Teknik Üniversitesi (İTÜ) Mustafa İnan Library staff were most helpful despite the Covid-19 related lockdown.

1. E. Suess, *Das Antlitz der Erde Zweite Hälfte. Schluss des Gesamtwerkes* F. Tempsky, G. Freytag, Eds. (Dritter Band, Wien, 1909), p. 789, vol. III/2.
2. M. J. DeWit, L. D. Ashwal, "Preface—Convergence towards divergent models of greenstone belts" in *Greenstone Belts*, M. J. DeWit, L. D. Ashwal, Eds. (Clarendon Press, Oxford, 1997), pp. ix–xvii.
3. J. A. Donaldson, P. G. Eriksson, W. Altermann, "Actualistic versus non-actualistic conditions in the Precambrian sedimentary record: Reappraisal of an enduring discussion" in *Precambrian Sedimentary Environments: A Modern Approach to Ancient Depositional Systems*, W. Altermann, P. L. Corcoran, Eds. (Blackwell Science, Oxford, 2002), pp. 3–13.
4. W. B. Hamilton, "Earth's first two billion years—The era of internally mobile crust" in *4-D Framework of Continental Crust*, H. D. Hatcher, Jr, M. P. Carlson, J. H. McBride, J. R. Martinez-Catalan, Eds, (Geological Society of America Memoir 200, 2007), pp. 233–296.
5. J. F. Dewey, "The secular evolution of plate tectonics and the continental crust: An outline" in *4-D Framework of Continental Crust*, H. D. Hatcher, Jr, M. P. Carlson, J. H. McBride, J. R. Martinez-Catalan, Eds, (Geological Society of America Memoir 200, 2007), p. 1.
6. K. Benn, J.-C. Mareschal, K. C. Condie, Eds., *Archaean Geodynamics and Environments* (Geophysical Monograph, American Geophysical Union, Washington, DC, 2006), vol. 64, pp. 1–320.
7. K. C. Condie, V. Pease, *When Did Plate Tectonics Begin on Planet Earth?* (Geological Society of America, Boulder, CO, 2008), p. viii-1–294.
8. L. B. Harris, J. H. Bédard, "Crustal evolution and deformation in a non-plate tectonic archaean earth: Comparison with Venus" in *Evolution of Archean Crust and Early Life*, Y. Dilek, H. Furnes, Eds. (Springer, Dordrecht, 2014), pp. 215–291.
9. K. Burke, J. F. Dewey, W. S. F. Kidd, "Dominance of horizontal movements, arc and microcontinental collisions during the later permobile regime" in *The Early History of the Earth*, B. F. Windley, Ed. (John Wiley & Sons, London, New York, 1976), pp. 113–129.
10. Ontario geological survey, "Map 2484 Lithostratigraphic Map of the Abitibi Subprovince" in Evolution of Archean Supracrustal Sequences, L. D. Ayres, P. C. Thurston, K. D. Card, W. Weber, Eds. (Geological Association of Canada, 1985).
11. R. S. Hildebrand, P. F. Hoffman, S. A. Bowring, The Calderian orogeny in wopmay orogen (1.9 Ga), northwestern Canadian shield. *Geol. Soc. Am. Bull.* **122**, 794–814 (2010).
12. S. M. Reddy, D. A. D. Evans, "Palaeoproterozoic supercontinents and global evolution: Correlations from core to atmosphere" in *Palaeoproterozoic Supercontinents and Global Evolution*, S. M. Reddy, R. Mazumder, D. A. D. Evans, A. S. Collins, Eds., Geological Society, London, Special Publications 2009), vol. 323, pp. 1–26.
13. V. A. Melezhik, L. R. Kump, E. J. Hanski, A. E. Fallick, A. R. Prave, "Tectonic evolution and major global earth-surface palaeoenvironmental events in the Palaeoproterozoic" in *Reading the Archive of Earth's Oxygenation, v. 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia–Drilling Early Earth Project*, V. A. Melezhik, Ed., (Springer, 2012), pp. 3–21.
14. C. Kilian, "Essai de la synthèse de la géologie du Sahara sud Constantinois et du Sahara Central telle qu'elle se présente à ce jour avec les changements apportés aux connasainces antérieures par les observations faites au cours de notre mission de 1922" in Congrès Géologique International—Comptes Rendus de la XIIIe Session, en Belgique, (Vaillant-Carmanne, Liége, 1925), pp. 887-944. 1922, deuxième fascicule.
15. P. R. Johnson, "Explanatory notes to the map of the proterozoic geology of western Saudi Arabia" (Tech. Rep. SGS-TR-2006-4, Saudi Geological Survey, Jeddah, 2006), p. 62.
16. J. R. Vail, "The Precambrian tectonic structure of north Africa" in *The Geology of Libya*, M. J. Salem, A. M. Sbeta, M. R. Bakbak, Eds. (Elsevier, Amsterdam, 1991), vol. VI, pp. 2259–2268.
17. P. R. Johnson *et al*., Late Cryogenian–Ediacaran history of the Arabian–Nubian shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern east African orogen. *J. Afr. Earth Sci.* **61**, 167–232 (2011).
18. Z. Hamimi, A. El-Barkooky, J. Martínez-Frías, H. Fritz, Y. Abd El-Rahman, Eds., *The Geology of Egypt* (Springer, Cham, 2020), p. 711. Regional Geology Reviews.
19. J.-P. Liégeois, "A new synthetic map of the Tuareg shield: An overview of its global structure and geological evolution" in *The Geology of the Arab World—An Overview*, A. Bendaoud, Z. Hamimi, M. Hamoudi, S. Djemai, B. Zoheir, Eds. (Springer Geology, Springer, Cham, 2019), pp. 83–107.
20. B. F. Windley, M. J. Whitehouse, M. A. O. Ba-Bttat, Early Precambrian gneiss terranes and pan-African island arcs in Yemen: Crustal accretion of the eastern Arabian shield. *Geology* **24**, 131–134 (1996).
21. R. J. Stern, A. Kröner, R. Bender, T. Reischmann, A. S. Dawoud, Precambrian basement around wadi Halfa, Sudan: A new perspective on the evolution of the east Saharan craton. *Geol. Rundsch.* **83**, 564–577 (1994).
22. V. Kazmin, Tektonicheskoe Razvitie Mozambigskogo poyasa: Ot akkretsii k kolizii. Геотектоника **3**, 26–34 (1988).
23. M. G. Abdelsalam, J.-P. Liégeois, R. J. Stern, The Saharan metacraton. *J. Afr. Earth Sci.* **34**, 119–136 (2002).
24. J. P. Liégeois, M. G. Abdelsalam, N. Ennih, A. Ouabadi, Metacraton: Nature, genesis and behavior. *Gondwana Res.* **23**, 220–237 (2013).
25. R. Black, J.-P. Liégeois, Cratons, mobile belts, alkaline rocks and continental lithospheric mantle: The Pan-African testimony. *J. Geol. Soc. London* **150**, 89–98 (1993).
26. D. E. Karig, Material transport within accretionary prisms and the "knocker" problem. *J. Geol.* **88**, 27–39 (1980).
27. K. Sieh, D. Natawidjaja, Neotectonics of the Sumatran fault, Indonesia. *J. Geophys. Res.* **105**, 28295–28326 (2000).
28. R. Hall, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations. *J. Asian Earth Sci.* **20**, 353–431 (2002).
29. EMAG3, NGDC's candidate for the world digital magnetic anomaly map. https://geomag.us/models/wdmam.html. Accessed 10 April 2020.
30. R. J. Stern, P. Johnson, Continental lithosphere of the Arabian plate: A geologic, petrologic, and geophysical synthesis. *Earth Sci. Rev.* **101**, 29–67 (2010).
31. S. Brahimi, J. P. Liégeois, J. F. Ghienne, M. Munschy, A. Bourmatte, The Tuareg shield terranes revisited and extended towards the northern Gondwana margin: Magnetic and gravimetric constraints. *Earth Sci. Rev.* **185**, 572–599 (2018).
32. A. M. C. Şengör, B. A. Natal'in, V. S. Burtman, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature* **364**, 299–307 (1993).
33. A. M. C. Şengör, B. A. Natal'in, G. Sunal, R. van der Voo, The tectonics of the Altaids: Crustal growth during the construction of the continental lithosphere of central Asia between ~750 and ~130 Ma ago. *Annu. Rev. Earth Planet. Sci.* **46**, 439–494 (2018).
34. H. Schandelmeier, A. Richter, G. Franz, Outline of the geology of magmatic and metamorphic units between Gebel Uweinat and Bir safsaf (SW Egypt/NW Sudan). *J. Afr. Earth Sci.* **1**, 275–283 (1983).
35. H. M. E. Schürmann, *The Precambrian in North Africa* (E. J. Brill, Leiden, 1974), pp. XVI, 351.
36. A. J. Bumby, R. Guiraud, The geodynamic setting of the Phanerozoic basins of Africa. *J. Afr. Earth Sci.* **43**, 1–12 (2005).
37. N. G. Obaje, *Geology and Mineral Resources of Nigeria* (Lecture Notes in Earth Sciences, Springer, Dordrecht, 2009), p. 221.

38. D. Thiéblemont, Y. Callec, M. Fernandez-Alonso, F. Chène, "A geological and isotopic framework of Precambrian terrains in western central Africa: An Introduction" in S. Siegesmund, M. A. S. Basei, P. Oyhantçabal, S. Oriolo, Eds., *Geology of Southwest Gondwana*, (Springer, Cham, 2018), pp. 107–132.
39. K. Burke, L. D. Ashwal, S. J. Webb, "New way to map old sutures using deformed alkaline rocks and carbonatites" in *Geology*, (2003), vol. 31, pp. 391–394.
40. A. R. Wooley, 2001, *Alkaline Rocks and Carbonatites of the World Part 3: Africa* (The Geological Society, London, 2001), pp. i, 372.
41. R. Caby, J. M. L. Bertrand, R. Black, Pan-African ocean closure and continental collision in the Hoggar-Iforas segment, central Sahara. *Develop. in Precambrian Geology* **4**, 407–434 (1981).
42. R. Caby, Precambrian coesite from northern Mali: First record and implications for plate tectonics in the trans-Saharan segment of the pan-African belt. *Eur. J. Mineral.* **6**, 235–244 (1994).
43. Z. X. Li *et al*., Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precambrian Res.* **160**, 179–210 (2008).
44. H. E. Gaudette, P. M. Hurley, Where were the pan-African mountains? No evidence of 500 M.Y. Detrital zircons. *Tectonophysics* **54**, 211–230 (1979).
45. U. Linnemann *et al*., Sands of west Gondwana: An archive of secular magmatism and plate interactions—A case study from the Cambro- Ordovician section of the Tassili ouan ahaggar (Algerian Sahara) using U–Pb–LA-ICP-MS detrital zircon ages. *Lithos* **123**, 188–203 (2011).
46. D. Avigad, R. J. Stern, M. Beyth, N. Miller, M. O. McWilliams, Detrital zircon U–Pb geochronology of Cryogenian diamictites and lower paleozoic sandstone in Ethiopia (Tigrai): Age constraints on neoproterozoic glaciation and crustal evolution of the southern Arabian–Nubian shield. *Precambrian Res.* **154**, 88–106 (2007).
47. N. L. Celli, S. Lebedev, A. J. Schaeffer, C. Gaina, African cratonic lithosphere carved by mantle plumes. *Nat. Commun.* **11**, 92 (2020).
48. D. P. McKenzie, The structure of the lithosphere and upper mantle beneath the Eastern Mediterranean and Middle East. *Mediterranean Geoscience Reviews*, 10.1007/s42990-020-00038-1 (2020).
49. M. Sobh *et al*., The lithospheric structure of the Saharan metacraton from 3-D Integrated geophysical-petrological modeling. *J. Geophys. Res. Solid Earth* **125**, e2019JB018747 (2020).
50. R. M. Shackleton, The final collision zone between east and west Gondwana: Where is it? *J. Afr. Earth Sci.* **23**, 271–287 (1996).
51. N. Lom, G. Sunal, N. G. Sağdıç, A. M. C. Şengör, "The Protogonos: a long-lived magmatic arc along the northern margin of Gondwana-Land and its disruption during the Hercynian Orogeny" in *Geological Society of America Abstracts with Programs*, (*Geological Society of America*, 2017) vol. **49**, p. 6.
52. A. M. C. Şengör, "Lithotectonic terranes and the plate tectonic theory of orogeny: A critique of the principles of terrane analysis" in *Terrane Analysis of China and the Pacific Rim: Houston*, T. J. Wiley, D. G. Howell, F. L. Wong, Eds., Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 1990), vol. 13, pp. 9–44.
53. A. Reymer, G. Schubert, Phanerozoic addition rates to the continental crust and crustal growth. *Tectonics* **3**, 63–77 (1984).
54. T. H. Torsvik, L. R. M. Cocks, *Earth History and Palaeogeography* (Cambridge University Press, 2017), p. 317.
55. J. R. Boyden *et al*., "Next-generation plate-tectonic reconstructions using GPlates" in *Geoinformatics*, R. Keller, C. Baru, Eds. (Cambridge University Press, Cambridge, UK, 2011), pp. 95–114.
56. A. M. C. Şengör, B. A. Natal'in, "Phanerozoic analogues of archaean oceanic basement fragments: Altaid ophiolites and ophirags. In Precambrian ophiolites and related rocks" in *Dev. Precambrian Geol. 13*, T. M. Kusky, Ed. (Elsevier, Amsterdam, 2004), pp. 675–726.